AD-A241 645

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704 0188

...mated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, ...d reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this ...s burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson ...e Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED FINAL, 01 Jan 87 to 30 Jun 91

4. TITLE AND SUBTITLE
NONLOCAL METHODS FOR SIGNAL DETECTION AND ESTIMATION IN THE DEPENDENT NONSTATIONARY ENVIRONMENT

5. FUNDING NUMBERS
AFOSR-87-0087
61102F, 2304/A6

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8. PERFORMING ORGANIZATION REPORT NUMBER
AFOSR-TR- 91 0799

9. SPONSORING MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFOSR/NM
Bldg 410
Bolling AFB DC 20332-6448

10. SPONSORING MONITORING AGENCY REPORT NUMBER
AFOSR-87-0087

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

We have obtained a number of results pertaining to image compression, robust estimation, and robust signal detection. All of this work has admitted the presence of data whose statistics are imperfectly known. Our results have featured adaptivity, flexibility, and non-traditional approaches. In order to employ more realistic statistical models, we have directed our research to admit non-stationarity and dependency. Much of our work in robust estimation and detection has employed a geometric approach which we have originated in past research. Our geometric techniques provide a quantitive way to measure the degree of robustness, thus offering the designer more flexibility in meeting the performance/robustness needs of the user. In addition, we have applied the geometric perspective to show how linear estimation algorithms can be modified to optimize a weighted combination of performance and robustness, thus offering the user the option of selecting various peformance/robustness combinations as deemed appropriate for a specific application.

14. SUBJECT TERMS	15. NUMBER OF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

"NONLOCAL METHODS FOR SIGNAL DETECTION AND ESTIMATION IN THE DEPENDENT NONSTATIONARY ENVIRONMENT"

FINAL REPORT FOR GRANT AFOSR-87-0087

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ABSTRACT

We have obtained a number of results pertaining to image compression, robust estimation, and robust signal detection. All of this work has admitted the presence of data whose statistics are imperfectly known. Our results have featured adaptivity, flexibility, and nontraditional approaches. In order to employ more realistic statistical models, we have directed our research to admit nonstationarity and dependency. Much of our work in robust estimation and detection has employed a geometric approach which we have originated in past research. Our geometric techniques provide a quantitive way to measure the degree of robustness, thus offering the designer more flexibility in meeting the performance/robustness needs of the user. Our results include generalized robustness criteria involving curvature as well as manifold slope, as well as generalized nonlocal robustness criteria which supersede prior nonlocal criteria based on the "worst case" perspective. In addition, we have applied the geometric perspective to show how linear estimation algorithms can be modified to optimize a weighted combination of performance and robustness, thus offering the user the option of selecting various performance/robustness combinations as deemed appropriate for a specific application.

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PUBLICATIONS SUPPORTED BY GRANT AFOSR-87-0087

1. M. W. Thompson and D. R. Halverson, "A Geometric Measure of Robustness Applied to a Nonstandard Class of Detectors," *Proc. 1987 Conf. on Information Sciences and Systems,* Baltimore, Maryland, March 25-27, 1987, pp. 348-353.

2. M. S. Schnitzer, D. R. Halverson, and M. W. Thompson, "Discrete Time Robust Detection of Stochastic Signals in Non-Gaussian Contaminated Noise," *J. Franklin Inst.*, vol. 324, pp. 19-25, July 1987.

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4. M. W. Thompson and D. R. Halverson, "A Differential Geometric Approach Toward Robust Signal Detection in Nonstationary and/or Dependent Noise," *Proc. Twenty-Fifth Annual Allerton Conf. on Communication, Control, and Computing*, Monticello, Illinois, September 30 - October 2, 1987, pp. 163-170.

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7. M. W. Thompson and D. R. Halverson (contributing authors), *Advances in Communications and Signal Processing* (edited by W. A. Porter and S. C. Kak). New York: Springer, 1989.

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9. D. R. Halverson, "Robust Estimation and Signal Detection in the Presence of Dependent Data," *Proc. 1989 Conf. on Information Sciences and Systems*, Baltimore, Maryland, March 22-24, 1989, pp. 283-288.

10. D. R. Halverson, "Alternative Criteria for Measuring Estimator Robustness," *Proc. 32nd Midwest Symposium on Circuits and Systems*, Urbana, Illinois, August 14-16, 1989, pp. 1158-1161.

11. C. Tsai, D. R. Halverson, and M. W. Thompson, "A Nonlocal Robustness Criterion for Signal Detection and Parameter Estimation," *Proc. 1990 Conf. on Information Sciences and Systems*, Baltimore, Maryland, March 21-23, 1990.

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SUMMARY OF RESEARCH

The research supported by Grant AFOSR-87-0087 has been primarily concerned with robust signal detection and estimation, although some effort has also been directed toward image compression. The latter research area will be addressed first.

A recently developed technique for image compression is Block Truncation Coding (BTC), a method which is easy to implement and often possesses good performance characteristics, relative to other approaches, even in the presence of many channel errors. In addition, the BTC algorithm does not depend on knowledge of the specific underlying statistical distributions but rather on sample moments. The basic BTC algorithm employs a two level quantizer whose output levels are obtained by matching sample moments. The image is divided into blocks of pixels, and the BTC algorithm is applied block by block. In some past work we have extended the basic BTC technique to a much more general setting which admits various options of implementation with the potential for improved performance. In our current work, we note that since various particular options seem most appropriate to certain image characteristics, the uniform application of one specific option across the entire image (as in earlier work) may not lead to best performance. Our current work illustrates an adaptive modification of the earlier BTC approach, which admits adjusting the algorithm on a block by block basis. While doing so, the algorithm chooses among various optional sample moments, as well as the options of "black on white" (higher numbers are assigned to lighter gray levels) or "white on black" (higher numbers are assigned to darker gray levels). We then show by example that such block by block adaptivity can lead to improved performance. Our work also shows that for the example images considered, the option employed across the entire image by the basic BTC algorithm is chosen by the adaptive algorithm for less than ten percent of the pixel blocks, thus illustrating the appeal of our adaptive approach. These results are delineated in #3 of the publication list.

A major thrust of our effort has been in the direction of robust signal detection. Some of our work has employed classical saddlepoint methodology to impart robustness. In some recent work we investigate a situation where inexact knowledge of the statistics of the noise is present for the discrete time detection of signals in i.i.d. non-Gaussian noise. In earlier work employing the canonical form of the locally optimal detector, some other authors showed how the design of the asymptotically robust detector for the Huber-Tukey mixture family of noises could be obtained. As might have been expected, the results led to censoring the factors of the test statistic to impart robustness, which led to the employment of a detector nonlinearity which limited observations of large magnitude. However, this work did not take into account the common situation where more is known about a noise density near the origin than on the tails. In fact, the noise often arises in practice from the sum of a number of "nearly" independent sources, and thus frequently the noise density resembles the Gaussian near the origin but may differ markedly on the tails. Such knowledge had the potential to be exploited for improved performance, where the robustness is imparted to account for our lack of knowledge of the tails of the noise density. We have investigated this opportunity and obtained results which specify an asymptotically robust detector for the situation where the noise density is known on an interval about the origin for the case where the signal is modeled as a random process. We then show by way of example that our robust detectors offer improved performance over the previous detectors; in fact, the improvement is quite dramatic in certain cases. These results are delineated in #2 of the publication list.

While classical saddlepoint techniques can be useful in investigating certain questions pertaining to robustness, we believe that the exceedingly heavy reliance placed by researchers on these techniques stems more from inertia and the apparent lack of suitable alternatives, rather than a universal recognition that saddlepoint techniques are ultimately suitable in all important respects. In our recent work, a desirable alternative has been developed which approaches the concept of robustness through a perspective based on differential geometry. While this approach has found application quite naturally to robust hypothesis testing, the core of signal detection, the approach also has the advantage of possessing the potential for wider domains of application. The geometric techniques employed allow the computation of a quantitative measure of the degree of robustness of a given detector subject to a wide variation of the underlying statistical distribution function about a nominal distribution. This new approach possesses distinct advantages when compared to classical saddlepoint criteria, which are inherently nonquantitative and are relevant to only a few restricted canonical regions of admissible variation about a nominal distribution. Moreover, the potential sacrifices in performance implied by the choice of a classical saddlepoint robust detector may be serious; some of our recent work, which completely specifies the classical saddlepoint robust detector for a signal in nominally Laplace noise, also shows that substantial sacrifices in performance are experienced. Our approach admits an analysis based on the quantitative tradeoff of performance and robustness, thus providing the user with a much more flexible design procedure than that based on the classical techniques.

The aforementioned geometric approach introduced by us has provided quantitative measures of the degree of robustness for both the local case, where the results have application only for small neighborhoods of distributions near the nominal, and the more general nonlocal case. These results have been applied to compare the robustness of a Neyman-Pearson optimal detector with a detector which employs a censored version of the Neyman-Pearson optimal nonlinearity, the form of the latter (hereafter called Huber-type) arising when classical saddlepoint methodology is utilized. In addition, the optimization of a weighted linear cost criterion of performance and robustness has been undertaken, with the results specifying the optimal censoring height of the detector nonlinearity. The accomplishment of such an undertaking would not have been an appropriate goal under the nonquantitative classical saddlepoint design methods, and the success of our geometric approach in addressing such goals has encouraged further investigations. The development of the geometric approach, together with several applications, has been summarized in #13 of the publication list.

Because our results have disclosed specific disadvantages as well as advantages of the Huber-type detector, we have recently investigated a more general nonstandard family of robust detectors; this family offers a more varied range of performance and robustness options. Our work considers both the local nonlocal situation, and we show that, by proper choice of the parameters associated with the nonstandard family, a much richer mix of performance and robustness is possible. These results are delineated in #1 of the publication list.

The aforementioned results using our geometric techniques have employed an assumption of i.i.d. data. While in some cases it may be appropriate to employ a sufficiently slow sampling rate to justify an assumption of independence, it is precisely in this kind of circumstance that stationarity assumptions become less credible. We therefore have recently considered removing the stationarity assumption in our geometric approach, and we have found that results analogous to the i.i.d. case are obtainable for both the local and nonlocal situation if one assumes independence without stationarity. One particularly interesting consequence of these results is that for many of the examples considered, the Huber-type robust detector becomes, like the Neyman-Pearson optimal detector, completely unrobust as the number of samples approaches infinity.

The robustness advantages of the Huber-type detector thus atrophy and approach zero for large numbers of samples, increasing the appeal of alternative nonstandard families of robust detectors. We have also undertaken an accompanying preliminary study of the effects of dependency, and our work shows how a measure of robustness can be developed for the case when the joint distribution function is parameterized by unknown parameters. One surprising consequence of these results is that we provide an example of a parameterized Gaussian family of joint distributions for which the linear detector is more robust than a corresponding censored linear (Huber-type) detector. Employment of a Huber-type detector may therefore do more harm than good if dependency is expected, and thus the classical robust detector is not at all "robust" to possible perturbations in the independence assumption. We also have investigated more general types of dependency, and our work shows that the definition for the robustness measure which is analogous to the corresponding definition in the independent case does not lead to a meaningful result. This difficulty arises because the required integrals fail to converge, presumably because there are too many allowable variations in the multidimensional distribution functions under consideration. A modification of our techniques for the general dependent case would thus be desirable. The aforementioned results are delineated in #4 of the publication list.

In some recent work, we have achieved a major breakthrough be accomplishing the aforementioned modification of our techniques, thus admitting application to the general dependent case. Our results provide a natural quantitative measure of the robustness of a signal detector with dependent data; this measure is sensitive to essentially arbitrary perturbations in an underlying joint distribution away from the nominal. Our results show, for example, that the presence of residual dependency can result in a reduction of robustness; in particular, this reduction is approximately 50% for the linear detector. Our work therefore shows, for the first time, precisely how serious the consequences of residual dependency can be. These results are delineated in #9 of the publication list.

In some other recent work, we have shown how our geometric techniques apply to a variety of signal processors. This work also includes results for measuring the robustness of a nonstandard family of signal detectors featuring nonempty "negative boundaries". This family is seen to offer the potential for enhanced robustness in certain situations over standard classical saddlepoint robust detectors and other detectors possessing empty "negative boundaries", thus opening the door for a more detailed analysis. These results are delineated in #6 and #7 of the publication list.

The aforementional work involving "negative boundaries" has recently been extended by us to include a comparison of the standard family of classical robust detectors to an important subfamily of the aforementioned nonstandard family. Using an optimized cost criterion that reflects the contribution of both performance and robustness, we show that when performance is emphasized then the standard family is most suitable; however, when robustness is emphasized then the nonstandard family is preferable. Our work thus allows the user to select a detector which most closely matches the desired performance/robustness mix. These results are delineated in #8 of the publication list.

Our current work also is directed toward the area of robust estimation. We have sought to apply the aforementioned geometric techniques to estimation as well as detection, and we have shown that this route can lead to success. As with signal detection, we desire a quantitative way to measure the degree of robustness of an estimator subject to lack of knowledge of the underlying statistical distributions. There appears to be more than a passing kinship between the areas of signal detection and estimation; both have optimal forms which arise under Radon-Nikodym derivatives, and both have robust forms which can be seen to arise under our geometric methodology. We have recently undertaken a quantitative analysis of the application of this methodology to robust parameter estimation, where general performance measures (including, but not limited to, mean square error) as well as nonstationary data are admitted. Our results show not only why censoring again can be helpful in imparting robustness, but also how limitations involving censoring can arise, including the atrophy of robustness for large numbers of samples. As with robust signal detection, our results facilitate the design of an estimator which trades off performance versus robustness subject to a cost criterion of interest of the user. These results are delineated in #5 of the publication list.

In conjunction with the aforementioned breakthrough admitting general dependent data in signal detection, we have also employed analogous modifications to our work in parameter estimation to allow measuring the robustness of an estimator of a random variable. Our work shows that the choice of performance fidelity criterion is crucial. For example, we find that for many popular error criteria (e.g. mean square error) *any* admissable estimator is completely unrobust. On the other hand, we also show that there exists a wide family of performance criteria for which some degree of robustness can be achieved. Somewhat surprisingly, in this case the best estimator has been shown by us to also often be the most robust. The conditional expectation estimator, known to be an optimal estimator under a variety of error criteria, thus can be either completely unrobust or optimally robust, depending on the choice of error criterion. The consideration of alternative error criteria to the popular mean square error criterion is therefore highly desirable. We have also exhibited success in generalizing our original geometric approach, which is local in nature, to the nonlocal arena by employing a "worst case" perspective analogous to that used with some success by the classical methodology. Our new nonlocal techniques, however, admit the consideration of essentially arbitrary regions about the nominal distribution, and can be used to draw nonlocal conclusions for a variety of important robustness questions, including how to control detector false alarm rate as the underlying distribution varies over a region containing the nominal. These results are delineated in #9 of the publication list.

An important family of estimators of a random variable is the family of linear estimators, which includes such popular algorithms as the Kalman-Bucy filter. Using the geometric approach, we have recently shown that, under fidelity criteria yielding nonzero robustness, the linear estimator which yields the best performance does not necessarily offer maximal robustness. This situation is therefore analogous to that for signal detection, where optimal performance (via a Neyman-Pearson test) and optimal robustness do not necessarily coincide. The user must, in such situations, judiciously trade off the two desirable attributes of performance of robustness, and we have accordingly shown how to accomplish this by designing an appropriate linear estimator which optimizes a corresponding cost criterion weighting the two attributes. Our results allow the user to specify robustness/performance mixes of 100%/0% all the way to 0%/100%. These results are delineated in #12 of the publication list.

We have also developed a new approach toward nonlocal robustness, which includes, but is not limited to, the "worst case" methods used by the classical approach and our geometric approach. This generalized nonlocal robustness criterion recognizes that the actual underlying distribution will very likely be neither nominal (as employed under optimal methods) nor least favorable (as employed under prior nonlocal robustness methods). Our generalized approach admits the employment of arbitrary weighted contributions of all distributions in the admissable family, and not just the least favorable. For example, a user might expect a greater likelihood that the actual distribution would be closer to the nominal than the least favorable, and might wish to incorporate such an assumption into the design of a robust scheme. Our work develops closed form expressions for generalized n.o. local robustness measures with application within both signal detection and estimation, using both linear and nonlinear weighting of the contributions of all distributions within the admissable family. These results are delineated in #11 of the publication list.

All of the aforementioned work which employs our recently originated geometric approach has been based on "first order" measures of robustness, wherein manifold slope is the key quantity. While such measures are suitable in many ways, we have found that on occasion two different detectors or estimators can have the same robustness under the operative "first order" measure. In such cases, more delicate measures are required, and we have succeeded in developing such measures through the introduction of a suitable choice of manifold curvature. Our work shows that these resultant measures reduce to two dominating terms, with the first yielding our existing operative "first order" measure, together with an additional "second order" term which allows differentiating between two detectors or estimators which have the same "first order" robustness. We have also shown by way of example that nonlinear processing of the data together with censoring can offer a 23% improvement in "second order" robustness when compared to linear processing with censoring, even though both the linear and nonlinear processing algorithms possess the same "first order" robustness. The employment of "second order" robustness is thus a useful auxiliary tool in the assessment of the sensitivity of an algorithm to inexact statistical knowledge. These results are delineated in #10 of the publication list.